



Enhancing Fracturing Proppant Performance: Methods and Assessment

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Abstract

The use of fracturing proppants is a key element of hydraulic fracturing operations in the oil and gas industry. The selection of proppants with superior performance is critical to ensure efficient and effective hydraulic fracturing. Proppant technologies are developing rapidly. Therefore, standardization of proppant evaluation is necessary to ensure accurate proppant evaluation during proppant production. Although the API and ISO have released a number of recommended practices for this purpose, there are still significant gaps in them. This is because several hypotheses regarding proppant performance, including proppant embedment and diagenesis, and their influence on proppant conductivity, are still not fully clear. Numerous proppants have been produced within the petroleum industry, featuring diverse compositions, sizes, shapes, and intended uses. While many proppants consist of silica or ceramics, there is growing interest in advanced types such as ultra-lightweight proppants. These innovations aim to minimize settling and enable transport using low-viscosity fluids. Moreover, to reduce expenditures, it is common practice in hybrid completions to mix proppant of different sizes according to stimulation design objectives and assumptions. Proppant can be equally mixed, separated by tail-in, or mixed with dominating concentrations of a specific size, depending on the type of fluids, viscosity, and anticipated settlement velocity. Surface modification involves altering the surface properties of the proppant to improve its adhesion to the fracture face and to reduce embedment and fines generation. Surface modification techniques include silane treatment, plasma treatment, and chemical treatment. The method can maintain oil flow channels after the hydraulic fracturing operation for a very long time. Proppant flowback, fines generation, and gel degradation are the key factors that contribute to a proppant pack losing permeability. Proppant pack conductivity can be increased, and well cleanup can be hastened, with the aid of a surface modification. This review paper aims to provide a comprehensive overview of proppant and its types, proppant performance assessment, and methods to enhance proppant performance. We discuss various techniques to evaluate proppant performance, including crush resistance, conductivity, embedment, and closure stress. Additionally, we highlight the importance of selecting the most appropriate proppant type for a particular well based on the formation properties and proppant characteristics. Furthermore, we explore recent advancements in proppant enhancement methods, such as coating, sintering, altering proppant surface, and consolidation, and their effectiveness in improving proppant performance. The comprehensive review provides insight into current industry practices and highlights potential areas for future research to improve fracturing proppant performance.

Keywords Proppant · Hydraulic fracture conductivity · Ceramic proppant · Resin coated sand

1 Introduction

Hydraulic fracturing method is a broadly used technique for hydrocarbons from low-permeability reservoirs extraction. Unconventional reservoirs are reservoirs with extremely low permeability (less than 0.1 mD) [1]. Unconventional reservoirs are those where natural gas cannot be produced economically as long as the well undergoes an extensive hydraulic fracture treatment, or horizontal, multilateral well-bores, or other methods are used to open up more of the

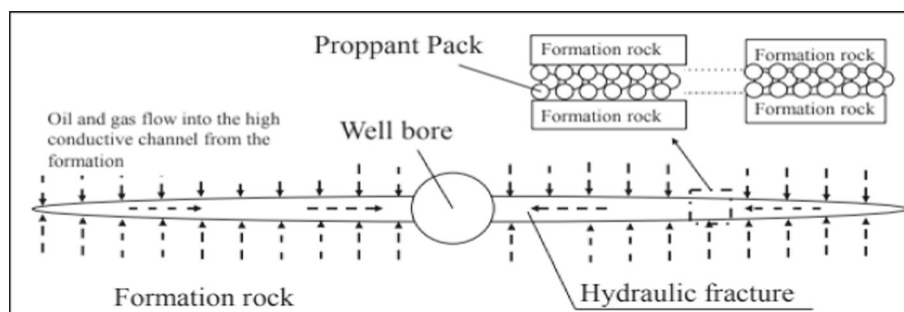
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Fig. 1 A schematic of the wellbore showing proppant packs placement in a hydraulic fracture (After Liu et al. [3])



reservoir to the wellbore [2]. The process involves pumping fracturing fluid at high pressure into the wellbore to create fractures in the formation, which are held open by proppants. Figure 1 illustrates a schematic cross-section of the wellbore showing proppant pack within the fracture.

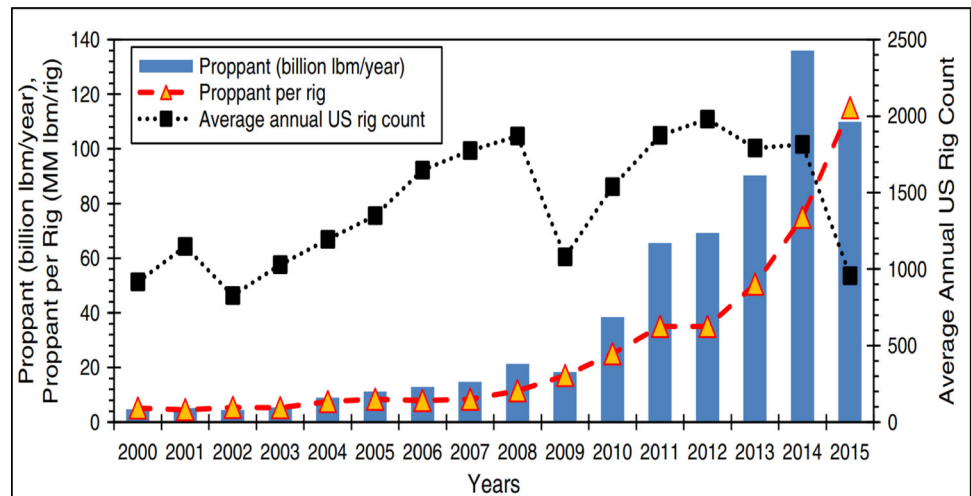
Fracturing proppants are solid materials, typically sand, ceramics, or resin-coated proppants, which are designed to hold the fractures open and allow hydrocarbons to flow to the wellbore. Proppant selection is crucial to ensure the effectiveness of hydraulic fracturing operations [1, 4]. The application of hydraulic fracturing, which was first utilized in 1947 on a gas well located in the Hugoton field in the USA, has been steadily expanding, and it is now extensively used by the petroleum sector for reservoir stimulation, which increases the output of oil or natural gas [5]. The use of horizontal drilling and hydraulic fracturing has made it possible to extract oil and gas from rocks that have very low permeability [6]. The global use of proppant is illustrated in Fig. 2. The proppant for the initial hydraulic fracture stimulations was river sand that had not been properly processed. Since this initial proppant experiment, the industry has developed a wide array of proppant options, while natural sand continues to be by far the most popular proppant for a number of reasons [7]. Hydraulic fracturing involves fluid flow, rock deformation and fracture growth. The fracture expands during the stage of injection, but it may shut if the injection is stopped, losing huge fraction of the obtained conductivity of the newly developed flow channels. To keep the channels open, proppants are typically added to frac fluid. The proppant particles should remain in situ to prevent cracks from closing and to maintain the constructed flow route during the production phase as the fracturing fluid flows back after pumping is complete. The ultimate proppant distribution in the fractured area is therefore crucial for the efficient fracture network [8]. A range of proppant types with varying sizes, shapes, and compositions are available, and selecting the optimal proppant type for a particular formation is a complex decision. Moreover, understanding the current technologies to enhance the performance of proppant is crucial for the optimum selection.

Limited number of studies in the literature explored in depth specific proppant aspects. For instance, comprehensive reviews were conducted over advancements in proppant technologies and selection criteria [1], advancements in lightweight proppant [9], and applications for polymers coating to enhance proppant performance [10]. Nevertheless, there is a lack of comprehensive review for the various proppant characteristics evaluation, and the current enhancement technologies to proppant performance. This review paper provides a summary of different types of proppants; proppant performance assessment, and methods to enhance proppant performance. The review aims to provide insight into current industry practices and highlights potential areas for future research to improve fracturing proppant performance.

Proppants are a granular material designed to hold open fractures created by hydraulic fracturing. The most common types of proppants are silica sand, ceramic proppants, and resin-coated proppants. Silica sand is the most widely used type of proppant and is inexpensive, abundant, and has a high conductivity rate. Ceramic proppants are more durable and have higher crush resistance than silica sand, making them more suitable for use in deep wells and high-stress formations [1].

The development of resin-coated sand aimed to increase the conductivity of frac sand due to its fragility, which produces fines under high pressure. Resin-coated sand (RCS) enhances the durability of proppant grains by distributing pressure more evenly, and it has the ability to encapsulate fractured grain fragments, effectively preventing their migration back to the wellbore. The size and shape of the proppant also play a critical role in determining its effectiveness. Proppant size is typically measured in terms of its mesh size, which refers to the number of openings per linear inch on a sieve. Typically, the size of proppant ranges from 105 μm to 2.38 mm (8–140 mesh) [1]. The utmost common mesh sizes for silica sand range are from 20/40 to 100/200. For instance, with 20/40 proppant, more than 90% of particles goes through 20-mesh sieve and held by the 40-mesh sieve [11]. Common method to determine the mesh size is dry sieve analysis [1, 12]. Higher fracture conductivity is typically provided by bigger particle sizes. The goal of the conventional

Fig. 2 Global use of proppant
(Mittal et al. [6])



fracture treatment is to increase the conductivity close to the wellbore by starting with smaller particle size at the far fracture end, and adjusting with larger proppant particle size close to the wellbore. In hybrid completions different particle sizes are mixed according to the requirements and assumptions of the simulation design. Proppant may be sorted by tail-in, blended equally, or blended with predominant concentrations of one specific size according to the treatment fluids, viscosity, and anticipated settling rates. One of the important things that should be considered when assessing the conductivity of the proppant pack is fine migration [13]. The standard conductivity test in the laboratory does not account for conductivity loss as a result of fines migration [14]. In order to determine the effect of fines migration, conductivity test should be conducted at a higher flow rate [13]. The proppant shape can also influence its performance, with more spherical proppants having better flow characteristics and higher conductivity than angular proppants [15, 16]. Enhanced sphericity not only improves porosity and permeability within the proppant pack, facilitating the flow of hydrocarbons through the fracture network, but also reduces turbulence during the transportation of grains through the fracking fluid due to their spherical form [11].

The properties of the formation being fractured, such as the permeability and closure stress, also influence the selection of the appropriate proppant type and size. The choice of proppant can have a significant impact on the overall effectiveness of the hydraulic fracturing operation, making it a critical decision for oil and gas companies.

2 Proppant Types

There are several types of fracturing sand that are commonly used in hydraulic fracturing operations. The most widely

used types are silica sand, ceramic proppants, and resin-coated proppants [4, 8, 17].

2.1 Silica Sand

Silica sand is the most common type of proppant and is made from natural quartz rock. It is inexpensive, readily available, and has a high conductivity rate, making it an ideal choice for hydraulic fracturing operations. However, its low crush resistance can lead to the production of fines, which can reduce the effectiveness of the proppant and clog the formation [10]. Silica sand is often not utilized directly from the mining without processing. For optimal performance, it goes through further treatment such as removing material from sand, breaking, washing and sizing the silica grains. Silica sand comes in two main varieties: white and brown. The Midwest area of the US provides the majority of the geological formations from which white sand is extracted. These sands are sometimes referred to as “white sand” due to their light tint which results from having higher silica content and minimal contaminants. Brownish appearance of the sand results from the higher impurity concentration, which also causes it to be less expensive and more vulnerable to crushing under light loads [1].

Requirements for frac sand include high silica content, medium to coarse particle size, roundness of at least 0.6 [18], strong crushing resistance, poor solubility and turbidity. Most of the frac sand used in the industry has a silica content between 95 and 99%, although premium frac sand has silica content of more than 99% of silica or quartz. Mature sand or sandstone that has undergone extensive processing and sorting, dissolving or removing less mechanically and chemically resistant minerals and sand particles, is known for its mineralogically pure silica content. The most desired resources of frac sand are unconsolidated loose sand or weakly consolidated sandstones, which may be mined with



huge excavators and do not require blasting during excavation or crushing during treatment [11]. Sand makes an excellent proppant for the majority of HF treatments due to its availability, low specific gravity, roundness, and low cost. Although the closure stress in the formation rises with depth, it has been discovered that when closure stresses approach 6,000 psi, fracture conductivity quickly degrades [10].

2.2 Ceramic Proppant

Ceramic proppant exhibits greater strength and resistance to crushing as compared to silica sand, particularly in situations where closing stresses are more than 10,000 psi [1]. Ceramic proppants are made from a mixture of clay and other materials, and are heated to high temperatures to create a hardened material that is more durable and crush-resistant than silica sand. They are also more uniform in size and shape, which can improve conductivity and reduce the amount of fines produced during hydraulic fracturing operations. However, they are more expensive than silica sand, making them less economical in some cases. Based on the strength, ceramic proppants are divided into three groups: high density ceramics (HDC), intermediate density ceramics (IDC) and lightweight ceramics (LWC) with densities of 3.5 g/cm³, 3.27 g/cm³ and 2.5–2.7 gm/cm³, respectively [8]. The high strength of ceramic proppants is due to alumina content. For the majority of ceramic proppants, the pellet density is primarily determined by the alumina content in the raw materials. LWC typically have 45–50% alumina, IDC have 70–75% alumina, and HDC contain 80–85% alumina [19]. However, even when the alumina concentration was increased to over 100%, the conductivity performance could not be improved to the desired levels. In order to produce very spherical, mono-sized, totally densified particles with high alumina content, they designed a novel manufacturing method. These proppants, also known as ultra-high-strength proppants (UHSP), and can withstand closure stress of 20,000 psi [19].

2.3 Resin-Coated Proppant

Resin-coated proppants (RCP) are similar to ceramic proppants, but are coated with a resin to improve their strength and reduce the amount of fines produced during hydraulic fracturing operations. The resin coating can also control the release of the proppant and prevent it from flowing back into the wellbore. The main benefit of resin-coated proppants is that it can hold fragments of fractured grain, limiting flowback to the wellbore [20]. As polymers are used to make coating materials, they often have lower melting temperatures, which is the fundamental drawback of resin coatings. There are currently two types of RCP on the market: pre-cured and cured. Uncured resin systems often have weak mechanical

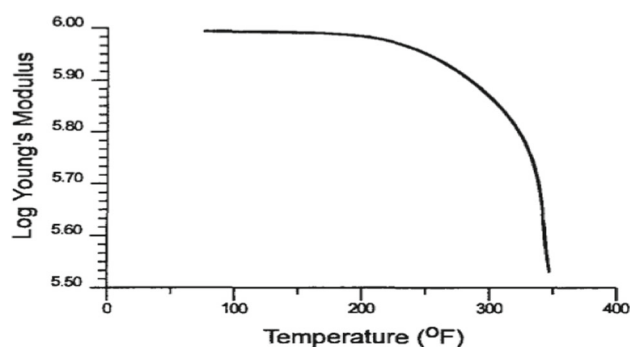


Fig. 3 Young's modulus versus temperature of epoxy resin with T_g of 300 °F (Dewprashad et al. [22])

characteristics. Nevertheless, by treating the linear resin with the suitable curatives to create crosslinked and 3D thermoset structures, desirable characteristics can be attained. This procedure is often termed as the curing process [1]. Precured proppant are covered at the manufacturing facility with fully or partially cured resin then pumping it into the well. Proppants do not clump together; rather, the formation stress in the area holds them together in the fracture. If the proppant is only half cured, the high temperature and pressure in the well completely cures the resin covering. Curable proppant is obtained by combining the proppant with a liquid resin system at the well site. Within the well formation, the crosslinking takes place under pressure and at a high temperature. The well is shut in after hydraulic fracturing to enable the curing process which will result in a consolidated proppant layer with each grain coated by resin. Chemical crosslinks will prevent the resin materials from melting when subjected to high temperature. However, when the temperature rises above glass transient temperature, the coating becomes soft, resulting in a decrease in strength [21]. The glass transition temperature (T_g) represents a specific temperature point at which amorphous polymers, in their glassy state, start to exhibit flexibility or a rubbery texture due to the initiation of segmental movement. This temperature marks the point where the stress/strain relationship ceases to be linear, undergoing a shift. As a result, the T_g of a polymer, like cured resin, corresponds to the point where the Young's modulus versus temperature graph changes direction (Fig. 3) [22].

It has been demonstrated that liquid resin-coated (LRS) function better at preventing flowback [23]. Due to poor bonding, proppant flowback utilizing resin-coated proppant (RCP) is frequently seen during the clean-up phase. In addition, flowback may happen following extended periods of proppant-free production, as a consequence of the damage caused by the repeated stresses imposed each time pumping is halted and resumed. When employing pre-cured proppant, not all of the resin is accessible for bonding between individual grains, resulting in minimal agglomeration. Conversely, LRS coating has the advantage of further curability, which

Table 1 Assessment of the different proppant types

Proppant type assessment		
Type	Advantages	Limitations
Silica sand	Cost effective (cheap)	Determines the particle size distribution, which impacts the proppant ability to maintain fracture conductivity and fluid flow.
	Readily available (Abundant)	Assesses the proppant chemical stability in acidic environments. High acid solubility can lead to the degradation of proppants.
	Chemical inertness High conductivity rate	Fines generation
Ceramic proppant	More durable than silica sand	Cost (more expensive compared to silica sand)
	Higher crush resistance (Higher strength)	Higher density
	Thermally stable	Limited availability compared to silica sand
Resin-coated proppant	Enhanced durability	Higher cost
	Encapsulate fractured grain fragments	Chemical compatibility

Table 2 Types of polymers used for proppant coating and their properties (modified after Zoveidavianpoor and Gharibi [10])

Polymer	Application temp (°F)	Strength	Heat resistance	Chemical resistance
Epoxy Resin	250–400	Good	Excellent	Good
Furan Resin	375	Poor	Moderate	Good
Polyester	212–300	Fair	Fair	Moderate
Urea Aldehyde	250–400	Good	Excellent	Good
Polyurethane	210–250	Good	Good	Moderate
Phenol-aldehyde	250–400	Good	Excellent	Good
Vinyl Esters	212–300	Fair	Fair	Moderate
Furfural Alcohol and Furfural	250–400	Good	Excellent	Good

contributes to its increased consolidation strength [21, 23]. Additionally, LRS exhibits ability to flow, thereby concentrating at the points of contact between grains. The inclusion of additives within LRS can inhibit chemical reactions with the components of the fracturing fluid. These characteristics collectively enhance the porosity and conductivity of proppants coated with LRS [21]. On the contrary, many shallow wells typically do not have enough pressure and temperature necessary for curing the proppant coating layer. As a result, using curable coated proppant might not be the best option. Pre-cured proppant is a more effective option in these circumstances for ensuring the fracture stays open throughout the stimulation of shallow wells [10]. The most commonly used resins used to coat proppants are epoxy resins, furan, polyesters, vinyl esters, and polyurethane. Epoxy resin is the main type of polymer which is used for proppant coating,

mainly because it has very good mechanical strength, excellent heat resistance and chemical resistance. Furan resin is another type of polymer used for proppant coating. Furan has great resistance to heat and water. However, furan does not provide enough mechanical strength. Polyurethane is another type of polymer which can be used for coating proppant. It can provide great mechanical strength, good heat resistance and chemical resistance when the application temperature is below 250 °F [1, 10]. The choice of proppant type and size highly depends on various factors, including the properties of the formation being fractured, the depth of the well, and the type of fracturing fluid being used [24]. Oil and gas companies must carefully consider these factors in order to select the most appropriate proppant for their hydraulic fracturing operations. Table 1 summarizes the major proppant types



with their advantages and limitations and Table 2 lists the various resins with their properties.

3 Proppant Performance Assessment

Proppant performance is typically evaluated based on a number of key factors including conductivity, crush resistance, embedment, and fines generation. Conductivity refers to the ability of the proppant to allow fluids to flow through the formation, while crush resistance refers to the ability of the proppant to withstand the high stresses and pressures of the hydraulic fracturing process without breaking down. Embedment refers to the extent to which the proppant becomes embedded in the fracture face, and fines generation refers to the amount of fine particles produced by the proppant during the fracturing process.

Various techniques have been developed to assess proppant performance, including proppant pack permeability and conductivity testing [25], crush resistance testing and acid solubility testing [26]. Proppant pack permeability testing involves measuring the ability of the proppant to allow fluids to flow through the formation, while conductivity testing involves measuring the ability of the proppant to conduct fluids through the fracture face. Crush resistance testing involves applying pressure to the proppant to measure its ability to withstand the stresses of the hydraulic fracturing process.

There are also numerous models and simulations that can be used to appraise proppant performance, including hydraulic fracturing simulators and fracture conductivity models. These tools can be used to predict how diverse types of proppant will perform in specific reservoirs and to optimize the hydraulic fracturing process to improve well productivity.

Proppant performance assessment is an important aspect of hydraulic fracturing operations, as it helps to ensure that the right proppant is selected for the formation being fractured and that the fracturing process is optimized for maximum well productivity. The API Recommend Practice (RP) 19C is the most recent version of the recommended practices for assessing proppant characterization [18]. These practices are: sieve analysis, sphericity/roundness, turbidity, acid solubility, density, loss on ignition and crush resistance.

3.1 Size and Shape

Sieve analysis and determination of grain diameter are outlined in the API recommend practice 19C [18] and requires that at least 90% of the proppant pass through the coarser screen while remaining on the finer screen. For example, with a 20/40 screen distribution, 90% of the proppant must pass through a 20 mesh but must be held at 40 mesh [15].

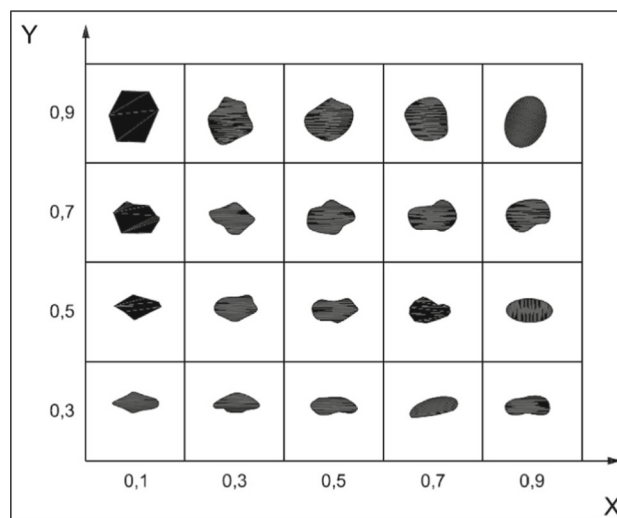


Fig. 4 Chart for sphericity (x) and roundness (y) estimation [1]

Particle size distribution can be measured by sieve analysis, dynamic light scattering (DLS), dynamic image analysis (DIA) or laser diffraction method. The two techniques were tested by [12]. It was concluded that both methods provide similar results for particle size up to 500 μm , but the results of laser diffraction method start to deviate from actual one for larger particles. It was advised to use sieve analysis for particle size measurements of granular particles with $D(90)$ higher than 500 μm . However, the reason of the deviation is that these two approaches measure different diameters of a particle. For example, sieve analysis frequently highlights the 2nd largest diameter due to the alignment requirements that particles must meet in order to pass through the mesh aperture. In contrast, laser diffraction measures equivalent diameter of a particle. For spherical particles both methods can be used to measure particle size throughout a wide range [12]. The conductivity and crush resistance of the proppant are strongly influenced by the sphericity and roundness of the proppant. They are improved with increasing sphericity and roundness. This is explained by more widespread stress distribution area [15]. When the form is circular and even, improved proppant packing may also result in higher conductivity. This is particularly true because conductivity is a function of pack width and permeability, both of which are influenced by the size as well as the shape of the proppant. Generally, sphericity and roundness of the particles are evaluated by comparing images of the proppant with the Krumbein and Sloss chart (Fig. 4). A more angular proppant is indicated by a lower Krumbein number. Proppant particles with angles and points have a propensity to break off points, which results in reduced conductivity at increased closure stress. ISO13503-2:2006 requires sphericity and roundness values at least of 0.7 for ceramic/resin-coated ceramic proppants and 0.6 for the other proppants [1]. Digital tools have

been utilized to analyze the size, roundness, and sphericity of proppant on a large scale. Examples include a dry dynamic particle analyzer and laser diffraction equipment [15].

3.2 Acid Solubility

The acid solubility is crucial for determining the proppant's chemical resistance. When mud acids—composed of hydrochloric and hydrofluoric acids—are employed to remove damage close to the wellbore, these acids might dissolve or even leach the chemicals on the proppant, endangering its structural stability and weakening it. The API RP 19C test for acid solubility involves submerging the proppant in a solution of HCl and HF at a 12:3 ratio. The amount of soluble substances such as carbonates, feldspar, iron oxides and clays that are contained in a proppant can be determined by the solubility of a proppant in the solution of 12:3 HCl:HF [18]. ISO 13503-2 specifies the maximum accepted solubility for sand, resin-coated proppants and gravel-packing sand proppants with a mesh size of 30/50 or larger as 2 wt%, and for those with a mesh size smaller than 30/50 as 3 wt%. For ceramic and resin-coated ceramic proppants maximum acid solubility by weight is 7 wt%. Acid solubility testing is conducted in 12:3 HCl:HF solution at temperature of 65 °C for a duration of 30 min. Acid solubility testing is conducted by adding 5 g of test proppant into 100 ml of acid solution at 65 °C. After acid treatment the sample should be placed in a filter, rinsed with water and dried at 105 °C in the oven [27, 28]. Acid solubility can be calculated by (Eq. 1):

$$S = \frac{M_s + M_f - M_{fs}}{M_s} * 100\% \quad (1)$$

where S is solubility, M_s is the mass of the proppant before, M_f is the mass of the filter and M_{fs} is the mass of the filter with the proppant after acid treatment.

It should be emphasized that API RP 19C is solely concerned with determining how well mineral separation methods can rid quartz sand of the soft and less desired cementitious materials. In HCl/HF combinations, the amorphous glass phases in addition to additional substances like magnetite, alkali metals, and ferric oxide that are typically present in ceramic proppant are also soluble in acid solutions [15]. As quartz sand is composed of monocrystalline silicon and does not include any glassy components, it can effectively withstand acid attacks. However, the poor strength and sphericity of quartz sand results in decreased fracture conductivity. On the other hand, ceramic proppant effectively resists HCl corrosion, but becomes susceptible to corrosion when exposed to a certain proportion of HCl-HF, limiting its application in the petroleum industry. The poor acid resistance primarily stems from silicon compounds in the raw material, since the silicon in the ceramic proppant is in an amorphous

form, making it vulnerable to HF-HCl acid solution [28]. In a study performed by Assem et al. [29] they investigated how sand and clay-based ceramic proppants performed when exposed to 12:3 HCl:HF acid at 300 °F. Crush resistance testing was performed on the proppants at 8,000 psi before and after being exposed to acid for 6 h. The authors observed that, following exposure to the acid, the compaction of clay-based proppants seemed to show a 6% increase, whereas sand proppants exhibited a smaller increase of about 1.5%. The greater acid solubility caused the clay-based proppant to lose its mechanical strength when exposed to acid, which had a significant impact on pack compaction system. Wu et al. [28] conducted a study on ceramic proppants produced in the Al_2O_3 - TiO_2 - BaCO_3 - MgO (ATBM) system. The impact of varying the BaCO_3/MgO ratio and the TiO_2 content on the proppant's tendency to dissolve in the 12:3 HCl:HF acid mixture was investigated. According to experimental findings, TiO_2 can be added to minimize acid solubility; 1 to 4 weight percent of TiO_2 is the most beneficial concentration. The minimum solubility of 0.13 wt% was obtained at 3 wt% of BaCO_3 ($\text{BaCO}_3:\text{MgO}$ —3:7) and 4 wt% of TiO_2 .

3.3 Proppant Conductivity

The effectiveness of the proppant can be revealed by conductivity tests. The fracture conductivity can be calculated by multiplying the fracture permeability to its width (Eq. 2). Like permeability, conductivity is not an inherent attribute of the material; rather, it is a reflection of a particular packing state and grain size distribution. It is used to calculate dimensionless form of fracture conductivity F_{CD} (Eq. 3).

$$\text{Conductivity} = K_{\text{frac}} * W_{\text{frac}} \quad (2)$$

$$F_{CD} = \frac{k_{\text{frac}} * w_{\text{frac}}}{k X_f} \quad (3)$$

where k_{frac} is the permeability of the fracture, w_{frac} is width of the fracture, k is the formation permeability and X_f is the half-length of the fracture, expressed in feet. After 8 years of preparation, the first standard for measuring conductivity of proppant, API RP 61, was released in 1989. The API RP 61 device (Fig. 5) was developed based on the system described by Cooke [30]. The suggested practice outlines guidelines that must be followed. Included in these conditions are running the test at room temperature, utilizing steel plates, deionized or distilled water, and imposing closure stresses for 15 min [6]. The procedure involves flowing a single-phase liquid at flow rates between 1 and 10 mL/min through a proppant pack cell size of $7 * 1 \frac{1}{2}$ in. Using the pressure drop values across ports that were close to the proppant, the permeability at a specific stress condition was calculated according to Darcy's law. The API RP 61 conductivity test



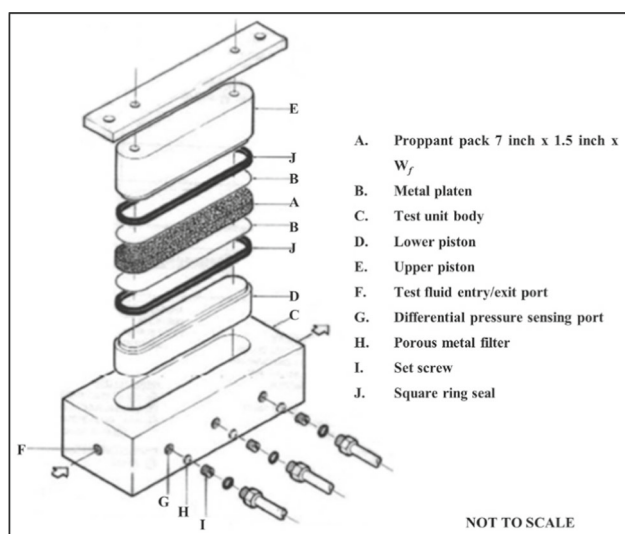


Fig. 5 API conductivity testing apparatus [31]

was regarded as a short-term conductivity test because there was no proppant settling. In most cases, the testing process calls for loading the cell with 2 lbs./ft² of proppant before gradually increasing the load in increments of 2000 psi and holding for 15 min at each stress level and the fluid flowed at rates of 2.5–10 mL/min.

Despite the API RP 61 testing guidelines, Cooke had already acknowledged the major influence that temperature and time under stress had on measured conductivities [30]. API RP 61 was replaced by ISO 13503-5 in 2006. When ISO 13503-5 was released in 2006, API RP 61 was no longer used for testing long-term conductivity. The equipment from API RP 61 is still used in the new technique, but several of the parameters have been updated to account for long-term testing. The time spent under stress was also altered to 50 h $\pm$ 2 h instead of only 15-min intervals in the short-term test. The short time in the short-term test does not allow for the proppant pack to stabilize under new stress. In order to allow for some embedment and lessen the wall slip region caused by the steel plates, they were replaced by Ohio sandstone. Several studies have acknowledged that temperature impacts the proppant pack performance, particularly because it alters the test fluid's viscosity, which is essential to the conductivity equation. As a result, ISO specified minimum test cell temperature of 250 °F for resin-coated and ceramic proppants and 150 °F for natural sand. Moreover, distilled water was replaced by silica saturated fluids [15].

3.3.1 Time Dependence

It has been reported by several authors that proppant conductivity under the stress is not stabilized in 50 h. To determine effect of time on conductivity of proppant pack, the “Proppant

Consortium” carried out tests wherein width and conductivity were assessed every 2.5 h during the course of testing that lasted 50 h [7]. The tests to measure the width and conductivity of the proppants were repeated three times with the same proppant sample and for each time the stack location of the proppants was changed to reduce the potential for bias in the test. By changing the position of each proppant for each repeat, the Consortium was able to increase the confidence in the results and ensure that any observed effects were not due to biases or artifacts in the experimental setup.

Regressions were carried out to match the data and data is plotted in semi-log graph. $\ln(x)$ represents the rate of conductivity change and the constant represents the conductivity at 1 h taken as initial conductivity. The data demonstrate that, over the test period of up to 50 h, the change in conductivity is log-linear. There is no sign of stability or the establishment of consistent conductivity. Moreover, the slope of the lines increases with stress. Analogous behavior was obtained from the results of experiment with sand and ceramic proppants showing a log-linear conductivity reduction over time with no sign of stabilizing after 50 h [7]. The results of these tests were used to build general equation (Eq. 4) for conductivity change with time:

$$K_f W_{f(t)} = K_f W_{f(t_0)} * (1 - M_t \ln(t)) \quad (4)$$

$K_f W_{f(t_0)}$ is conductivity at 1 h and M_t is the absolute value of the slope of normalized conductivity versus $\ln(t)$.

3.3.2 Cyclic Stress

The two main sources of fines are proppant and formation. As proppant gets embedded into the fracture face as a result of spalling, reservoir fines may be produced [32]. Proppant can also be broken and crushed into numerous tiny pieces. The produced fines will affect the porosity of the proppant pack, and fracture conductivity as well as productivity will be significantly affected. Often, a well goes through a cycle of being shut down and restarted during its lifetime. During this procedure, there is a rapid increase followed by a decrease in bottom hole pressure, leading to fluctuations in closure pressure and stress exerted on the proppant pack, which ultimately leads to a decrease in the conductivity of the proppant pack [33, 34]. Laboratory tests have shown that cycling can decrease the conductivity of proppant in a conductivity cell [35]. It has been proven by some authors that as the number of cycles increased, the generation of fines reduced [36]. This might indicate that the proppant was rearranging between cycles. In order to forecast how cycling affects the baseline conductivity, the Stim-Lab Proppant Consortium has tested a variety of proppants under various pressures [7]. The cycling tests were involved subjecting 20/40 and 16/30 sand to 25 stress cycles. In each cycle pressure was increased from 1,000



to 2,000 to 4,000 psi, maintained for 50 h and then returned to 1,000 psi. Sand conductivity was measured at both 4,000 and 1,000 pressure during each cycle, and the results revealed that the conductivity dropped with each cycle. The loss in conductivity during cycling can be modeled by a power law function given in Eq. 5 [7]:

$$\text{Conductivity with cycling} = \text{Conductivity at first cycle} * N^a \quad (5)$$

where N is the total number of cycles and a is the exponent of cycling.

3.4 Crush Resistance

Proppant crushing results from frac closure stress exceeding strength of proppant. This will result in fines formation and reduction in the width of fracture, which will ultimately reduce conductivity of the proppant pack. Throughout the course of a well lifespan, a proppant pack is subjected to several stress cycles. The proppant pack may shift, tire, and produce particles as a result of these stress variations, which will reduce conductivity. Moreover, as hydrocarbons are produced, proppant may also flow into the wellbore due to significant drag forces brought on by the high production rate. Proppant flowback can be avoided by coating the proppant with substances that, when cured at a specific temperature and pressure, establish bonds between the grains and prevent them from shifting. Moreover, it has the benefit of increasing crush resistance [10]. However, when RCP cannot withstand closure stress, the proppant will break and fines will be retained inside the coating. This will result in the deformation of proppant and subsequent reduction in porosity as illustrated in Fig. 6.

The standard for crush resistance establishes how much proppant will be crushed at a specific stress. The crush resistance test outlined in API RP 19C involves applying stress incrementally to the proppant pack until the crushed materials exceed 10 wt% of the total sample [18]. The material must have been sieved before the testing to ensure that the materials being tested are within the specified size range. Crushed proppants are then sieved and quantified as a percentage of the total weight of the material. However, the standards for crush test do not represent actual reservoir condition, are simplified and prone to human errors [37]. Duenckel et al. conducted a test to investigate how the reservoir environment affects the mechanical characteristics of proppants. Stainless steel cells with a 450 ml capacity were used. Each cell was filled with around 400 ml of proppant. Then, approximately 125 ml of deionized water or 2% KCl solution was added to fill the porosity between the grains and saturate the cell and the cell was placed in the oven. For a duration of 14 days,

Table 3 Increase in crush percentage over a 14-day period at 204 °C for three distinct proppant types exposed to different fluid conditions [38]

Proppant	Fluid	Increase in crushing %
20/40 HSC	Dry	11
20/40 HSC	Deionized water	21
20/40 HSC	2% KCL	37
20/40 LWC	Deionized water	61
40/80 LWC	Dry	16
40/80 LWC	Deionized water	26
20/40 Sand	Dry	30
20/40 Sand	Deionized water	43

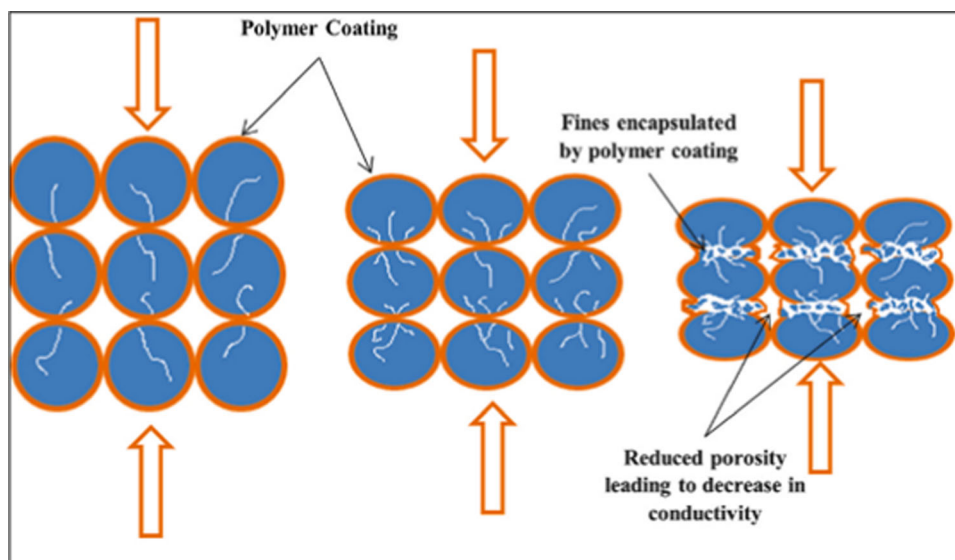
all proppants were subjected to 204 °C in deionized water, 2% KCl, and dry conditions. They demonstrated an increase in the crushing percentage for three distinct proppant types (Table 3), high-strength ceramic (HSC), lightweight ceramic (LWC), and sand. Comparing API crush test results before and after the static test, it was found that all of the proppants experienced an increase in crushing % when exposed to high temperature and solutions. When sand proppants interact with fracture fluids, they are more prone to crushing compared to other proppants. In contrast to LWC and sand proppants, HSC proppants exhibited less crushing in both dry and DI water scenarios, and when it came into contact with 2% KCl, its crush percentage rose to 37% [38].

3.5 Constraints and Drawbacks of Proppant Performance Assessment Methods

There is still much work to be done on the present standard approach for evaluating the properties of proppant because its process is still the subject of numerous theories. The existing process is constrained by a few factors. Although there have been various attempts over the years to alter the design of the conductivity test unit, there aren't many publications that go into great length on this. It might be explained by the current tendency among academics, who are concentrating on mathematical modeling and simulations, to forecast the performance of the proppant. The API standards only listed 2% (KCl) in a solution of deionized or distilled water as the test fluid. Although there is a good justification for the standardization, it is a poor simulation of actual fracturing fluid. The process of diagenesis reduces the conductivity of proppant pack, but this process is not clearly understood to apply it to the conductivity tests. Moreover, there are various design restrictions with the conductivity test cell such as proppant loading, sandstone core edge failure, temperature management, and uneven pressure distribution that must be taken into consideration [7]. Because manual loading leaves room for human error, automated loading tools must



Fig. 6 Coated proppant [15]



be developed in the future. A statistically substantial number of observations under identical packing circumstances and along similar loading routes are required for conductivity estimations. There are three factors that can cause discrepancies in laboratory conductivity results. These factors are: pack width variations, secondary alteration to pack width, and permeability variations. The original packing arrangement may be affecting how the material compresses and rearranges under increased loading, leading to variations in the width of the pack. Grain embedment, grain breakdown at contact points, and grain redistribution all cause secondary changes to pack width. Due to the complex and dynamic nature of proppant behavior under external forces, it can be difficult to precisely control all factors that may impact conductivity values. Nonetheless, it is commonly acknowledged that for a specific proppant type and size, conductivity values fluctuations of $\pm 20\%$ can be within the range of laboratory accuracy [39]. Table 4 summarizes the different proppant assessment methods.

4 Proppant Enhancement Methods

4.1 Coating with Polymers

Coating proppant is one of the most widely applied enhancement methods. This coating acts as a protective layer, preventing leakage and facilitating interaction between the proppant particles. Additionally, it helps to encapsulate any broken pieces of proppant. Polymers are synthesized by either polycondensation or addition polymerization of tiny monomers. Polymers can be categorized into organic polymers and inorganic polymers based on their chemical

composition. Organic polymers can be classified into two categories based on their heat behavior: thermosetting polymers and thermoplastic polymers. Thermosetting polymers are extensively utilized in proppant coating due to their numerous benefits, including convenient processing, superior strength, and reduced density [21]. However, thermosetting polymers have certain drawbacks such as limited resistance to oxygen, ozone, and radiation, as well as reduced thermal stability. Zoveidavianpoor and Gharibi provided a list of the primary polymers utilized in proppant coating, which includes epoxy resin, phenolic resin, urea-aldehyde, and others. Out of these polymers, epoxy and phenolic resin emerged as the most favorable options, mostly because of their exceptional performance and affordable price [10, 40].

4.1.1 Coating Methods

4.1.1.1 Thermoplastic Coating This type of coating enhances the proppant's ability to resist flow by increasing the contact area between the grains, hence imparting mechanical resistance to flow back. Proppant coatings can be made from thermoplastic polymers like polycarbonates, polyethylene, polybutylene, polyurethanes, polypropylene, polysulfones, polyimides, and cellulose derivatives. These coatings are applied to the proppant before it's inserted into the well formation using a hot coat technique. This process includes heating the proppant to a temperature above the thermoplastic material's melting point. The molten thermoplastic is then applied to coat the particles, and the fracturing fluid carries them into the fractures. The conductivity measurement of proppant and its critical flow return velocity is conducted in a simulated fracture flow cell. During the process of proppant transport, the proppant becomes trapped within the fractures together with the thermoplastic film.

Table 4 Assessment properties and testing methods of proppants

Proppant property assessment			
Property/performance assessment	Testing methods	Standardized test number	Importance/significance
Size and shape	Sieve analysis	ISO 13503-2, API RP 19C or API STD 19C	Determines the particle size distribution, which impacts the proppant ability to maintain fracture conductivity and fluid flow.
Chemical resistance	Acid solubility test	ISO 13503-2, API RP 19C or API STD 19C	Assesses the proppant chemical stability in acidic environments. High acid solubility can lead to the degradation of proppants.
Proppant conductivity	Conductivity test	ISO 13503-5, API RP 19D	Measures the ability of proppants to maintain permeability under stress, which is critical for ensuring sustained oil and gas flow.
Time dependence	Long-term conductivity test	Specific standardized test is not directly available; typically assessed through long-term conductivity tests under various conditions, referring to ISO 13503-5 and API RP 19D for extended duration tests	Evaluates how the proppant's conductivity holds up over time under reservoir conditions. This is vital for predicting long-term performance.
Cyclic stress	Cyclic loading test	No single standard test; evaluated through custom or modified versions of strength and crush resistance tests under cyclic loading conditions. Reference standards like ISO 13503-2 and API RP 19C for general guidance	Simulates the repeated stress cycles experienced in the reservoir, assessing proppant's durability.
Strength and crush resistance	Crush test	ISO 13503-2, API RP 19C or API STD 19C	Determines the ability of proppants to withstand high pressures without breaking. Higher crush resistance ensures that the proppants will not turn into fines, which can block fluid flow and reduce well productivity.
Sphericity and roundness	Visual inspection and sphericity/roundness chart	ISO 13503-2, API RP 19C or API STD 19C	High sphericity and roundness improve the packing of proppants in the fracture, enhancing permeability and reducing the risk of clogging.
Density	Pycnometer test	ISO 13503-2, API RP 19C or API STD 19C	Determines the mass per unit volume, impacting how the proppant is transported and settles in the fracture.

The elevated temperature inside the formation initiates the thermoplastic material softening, causing it to envelop the particles of the proppant and promote their clustering with adjacent particles of the proppant. Researchers found that the elevated temperature in the underground formation causes the coating on the proppant to clump together, creating a stable network of particles [41]. Other researchers demonstrated

that including thermoplastic films, at a concentration ranging from 0.01 to 15% of the proppant's weight, in the fracturing fluid reduces proppant flow back. Flow back occurred when sand was used as the sole material, at a fluid flow rate of 150 cc/min. Tests conducted on a mixture of sand and thermoplastic ribbon demonstrated that there was no reverse flow



of sand, even when the flow rate was as high as 500 cc/min [42].

4.1.1.2 Fluorinated Coating The porous and ceramic proppant, composed of either Si_3N_4 or SiC , possesses a notable capacity to withstand compression and exhibits a very low specific gravity. These characteristics greatly facilitate the transportation of the proppant [43]. Due to its lightweight nature, transporting it using a fracturing fluid that has a low viscosity can be easy, resulting in cost-effectiveness. Additionally, its high crush strength leads to a reduction of 10% in fines production. The crush strength of the material can vary between 2000 and 12,000 psi, while its specific gravity can range from 1.0 to 2.2 g/cc. An inherent drawback of using lightweight porous proppant is the potential for the fracturing fluid to infiltrate the proppant, hence altering its density and transport characteristics. Applying a layer of fluorinated siloxane or fluorinated polymer to the porous proppant decreases or stops the penetration [44]. Fluorinated materials possess a decreased surface energy and have exceptional thermal and chemical durability. When coated on proppants, it altered the way the proppant material interacts with liquids, making it both resistant to water and oil, and so unable to be wetted by the fracturing fluid. Remarkably, it enhanced the conductivity of oil and gas within the fractures, ultimately leading to an improvement in production. The decrease in effective fracture conductivity and well productivity can be linked to the lowering of non-Darcy behavior [45].

4.1.1.3 Inorganic Coating Utilization of inorganic coatings on proppant is highly restricted and typically necessitates exceedingly elevated sintering temperatures. Geopolymers are gels composed of alkali-activated aluminosilicates, which consist of Silicon–Oxygen–Silicon and Silicon–Oxygen–Aluminum bonds [46]. The polymerization commences with the liberation of aluminate and silicate monomers as a result of an alkali assault by an alkali metal hydroxide. The freed monomers undergo hydrolysis and subsequently engage in reactions to make dimers, which further react to form oligomers. This process continues until polymeric networks are ultimately generated. Urbanek utilized an inorganic binder composed of aluminum oxide and silicon dioxide as a covering for proppants. The user blended precise quantities of Al_2O_3 , SiO_2 , alkali fluoride complexes, and water. The mixture was then subjected to drying at a temperature of 100 °C, followed by curing at 375 °C. Due to their inorganic nature, these materials possess elevated compressive strengths, as well as exceptional chemical and thermal stabilities. The coating cures at a lower temperature than other inorganic coatings, allowing for the incorporation of temperature-sensitive additives and fillers into the formulation [47].

4.1.1.4 Hydrogel Coating Resin coatings can be costly and prone to detachment, which raises environmental concerns and can result in sedimentation. The choice between uncoated or coated proppant, as well as the specific type of coating, primarily relies on the circumstances present in the formation and the expertise of the petroleum engineer. While the benefits and constraints of various proppant types are widely recognized, achieving accurate proppant placement remains the utmost emphasis. Due to its greater density, sand has the ability to separate and sink during the process of insertion. The issue was resolved by applying a hydrogel covering to the proppant particle [48]. The hydrogel coating enhances the conveyance of proppants further into the well and fractures by inhibiting their premature sedimentation. Additionally, it reduces the requirement for a substance with high viscosity as the particle can be readily disseminated in a watery fluid. The hydrogel possesses friction-reducing characteristics that facilitate the smooth movement of the proppant into cracks. The system is considered cost-effective due to the removal of viscosifiers and friction-reducers, as well as the decrease in pumping energy and fluid sweeps. The study describes the initial coating of sand with poly-diallyl dimethylammonium chloride (PolyDADMAC), a cationic polymer. The sand that had been coated was subjected to a drying process, then combined with a liquid called Flopam EM533®, which is a copolymer consisting of high molecular weight acrylic acid and acrylamide. The mixture was then heated at a temperature of 80 °C for the duration of one night in order to eliminate any water or solvents present. PolyDADMAC forms an ionic interaction with Flopam EM355®, resulting in the stabilization of the coating layers. The settling test revealed that the uncoated sand settles at the bottom within 10 s, however the sand coated with hydrogel takes between 20 and 60 s to settle, depending on the concentration and thickness of the applied Flopam EM355 coating. The bed height in a stable state was also measured after being immersed in water for 30 min. The bed height of uncoated sand is recorded as 0.8 mm, whereas the bed height of coated sand varies between 6.9 and 22.9 mm.

4.1.1.5 Magnetic Coating To prevent proppant flowback, proppants are commonly coated with a thermoset resin that solidifies into a rigid mass inside the formation. Additionally, the prevention of flowback can be achieved by including magnetic elements into the proppant. As the magnetic material and proppant enter fractures, they form clusters of magnetic proppants that are kept together by a powerful magnetic force [49]. This arrangement hinders the backward movement of proppants while simultaneously preserving fluid channels that facilitate the flow of hydrocarbons. Iron, ferrite, low-carbon steel, iron-silicon alloys, nickel—iron alloys, iron-cobalt alloys, and other related metals are examples of magnetizable materials that can be utilized. A



technique for affixing magnetic particles onto the surface of the proppant is done by utilizing a polymeric adhesive binder [50]. The magnetite powder was combined with molten novolac resin, solidified, and subsequently divided into minute fragments. Subsequently, the magnetic resin and hexamethylenetetramine were introduced into preheated sand or ceramic proppant and let to cool. The cohesiveness of the proppant was evaluated in comparison to the traditional novolac coated ceramic proppant. Following a 45° inclination of a flat surface, the conventional proppant exhibited a tendency to roll off, whereas the magnetic proppant remained intact as a cohesive unit on the surface.

4.1.2 Reported Enhancements as a Result of Proppant Coating

Applying polymers as coatings to proppants augments their physical and chemical attributes and functionality, including but not limited to reducing density, enhancing sphericity, controlling flowback, bolstering chemical resistance, heightening affinity for hydrocarbons, augmenting fracture conductivity, and enveloping fractured portions of the proppant in the event of breakage. Several studies reported enhancement to various aspects of proppant performance. For instance, it was found that applying an organic polymer coating to standard proppants can reduce their density, enhance their sphericity and inhibit proppant flowback. Furthermore, it was found that applying a polymer coating to proppant can enhance its chemical resistance and hydrocarbon affinity [1, 21]. In the following sub-sections, we will present the reported enhancements to different types of proppants.

4.1.2.1 Natural Sand Polymer Coated Proppant Several studies examined the enhancement of polymer-coated sand proppant [51–58]. For instance, the influence of different polymer types, like epoxy furan, novolac, and resole resins, on the overall characteristics of coated sand was analyzed and showed that it ultimately improves the proppant quality in comparison to natural sand. The crushing rates had a significant reduction, dropping from 36% to below 4%. This decrease allows for the utilization of coated sand proppant in deep oil wells drilling. The solubility in acid was reduced to 0.5%, resulting in a significant enhancement in its ability to withstand strong acids used in fluids meant to clean fractures. The level of turbidity reduced from 95 to below 30, resulting in a reduction of proppant pollution in both soil and oil. The roundness and sphericity values experienced a rise from 0.6 to 0.8, resulting in an improvement in conductivity [58].

Various studies reported an enhancement in a specific proppant criterion when polymer is applied to natural sand. From a conductivity perspective, it was documented the acquisition of high-performance carbon nanotube (CNT)

toughened epoxy coated sand proppants exhibiting significantly enhanced conductivity [57]. Furthermore, Fu et al. [52] studied the enhanced flow back control and crack conductivity of a proppant made by coating sand with Poly(2-fluorine-4-vinylpyridine). Chen et al. [51] introduced phenolic/epoxy binary mixture-coated sand in their investigation of resin-coated sand proppants for production of oil, resulting in further enhancement of proppant sphericity and roundness from 6.5 to 0.85. Krishnan et al. [54, 55] explored multicomponent polymer-coated sand, comprising polystyrene, polymethyl methacrylate, and epoxy, achieving the production of very-low bulk density below 1.5 g/cm³, although notable improvements in crushing rate and sphericity were not evident.

Horadam et al. [53] produced novolac resin-coated sand to probe into its chemical stability under various settings, finding increased leaching behavior under high temperatures of 400 °C and severe acidic conditions with a pH of 3. The aqueous leachates were discovered to have a phenolics concentration of less than 1 ppm. Finally, Ramlan et al. [56] discussed the use of graphene oxide/silane coupling agent coated sand. They observed that although the overall performance was not significantly improved, the manufacturing process was rather simple.

4.1.2.2 Synthetic Ceramic Polymer Coated Proppant.

Reducing proppant density holds significant importance in enhancing the efficiency and effectiveness of hydraulic fracturing operations. Lower proppant density enables the creation of fractures with higher conductivity and stability, facilitating the flow of hydrocarbons from the reservoir to the wellbore. Additionally, decreased proppant density reduces the risk of proppant settling and embedment, ensuring long-term fracture conductivity and well productivity. Deng et al. [59] provided an in-depth examination of the manufacturing process of ceramic proppant, whereby manganese oxide, potassium feldspar and waste fly ash, were utilized in the sintering process. After applying an epoxy/phenolic binary mixture as a coating, the rate of crushing decreased from 20.3 to 3.76%, and density reduced from 3.11 to 2.64 g/cm³. Similarly, Xie et al. [60] produced a cost-effective ceramic proppant by combining kaolin with Zinc Oxide, resulting in a significant decrease in apparent density to 2.27 g/cm³ through the application of epoxy coating. In addition, Guo et al. [61] created a ceramic proppant called Phenolic-epoxy coated porous mullite-based ceramic proppant, that has a lower apparent density of 1.90 g/cm³. This proppant also improves compressive strength, roundness and sphericity.

The proppant's hydrophobic nature has a substantial impact on hydraulic fracturing effectiveness by decreasing water absorption and improving the oil flow as well as gas. Thus, increasing the hydrophobic nature of the proppant is



imperative. In their study, Fan et al. [62] investigated the utilization of the ceramic proppant (epoxy-coated) practically, which led to a significant 16-fold enhancement in the self-suspension capacity of the coated proppant. In addition, there was an 83.8% rise in hydrophobicity and a 16.71% increase in conductivity.

4.1.2.3 Bio-Based Nutshell Polymer Coated Proppant

Zoveidavianpoor and Gharibi [10] conducted a systematic analysis of the walnut, coconut and palm shells properties to determine the effectiveness of using untreated nutshell in hydraulic fracturing. The shells displayed apparent densities in the range of 1.14 to 1.33 g/cm³, having low turbidity, crushing speeds and acid solubility. Coated nutshell proppants were designed to address problems including heat resistance and inadequate corrosion and, namely the low roundness and sphericity of non-coated nutshell. Zoveidavianpoor et al. [9] conducted a study to examine the characteristics of coconut shell proppants that were coated with epoxy. The coated proppants exhibited a significant decrease in crushing rates, dropping from 2.12 to 0.16%. Additionally, they showed reduced turbidity and acid solubility, with respective values of 38 and 1.8. In addition, the roundness and sphericity values, respectively, increased to 0.8 from 0.7.

Li et al. [63] documented phenolic resin-coated nutshell particles, resulting in a proppant with an apparent density of 1.23 g/cm³. In their investigation, particles of nutshell in the range 20–40 mesh were consistently utilized. This proppant exhibited reduced adsorption of water to 17% from 30% and conductivity increase to 113.4 $\mu\text{m}^2\cdot\text{cm}$ from 41.8. Furthermore, Li et al. [64] conducted additional research on the impact of coating times on coated nutshell properties. They observed improvements in water adsorption and compression deformation properties, along with an increase in sphericity and roundness to 0.86.

4.1.3 Limitations and Challenges of Proppant Coating

While addressed for each coating technique, this section emphasizes on the limitations and challenges. In thermoplastic coating, the requirement for precise temperature control during application and deployment to ensure proper adhesion and performance is a limitation. If the temperature is too high, it can lead to excessive softening or degradation of the coating. However, insufficient heat may result in poor bonding and coverage.

While fluorinated coatings provide superior performance in resisting chemical attack, their inflexibility can result in brittleness, leading to potential cracking and failure under cyclic stress conditions. Inorganic coating may not bond as effectively as organic coatings. These coatings can as well add considerable weight to the proppants, affecting their transport and placement within the fractures.

Despite their innovative benefits, hydrogel coatings may not be used in saline and high temperature conditions, which can affect their swelling behavior and performance. The hydrogel coatings may degrade over time, losing their effectiveness and potentially releasing degradation productions into the environment.

The primary limitation of magnetic coatings is the cost and complexity of implementing magnetic field equipment at well sites. Ensuring uniform magnetic coating and maintaining the magnetic properties under downhole conditions can be difficult.

4.2 Sintering

Sintering is a heat treatment applied to powdered materials to form a solid mass of proppant particles through heat without melting to the point of liquefaction. Starting with selecting raw materials such as silica or bauxite, these are ground to powder and formed into pellets. These pellets are then dried to remove moisture, a critical step for efficient sintering. During the sintering phase, the granules are heated to a point where particles adhere without melting, facilitated by diffusion mechanisms. This process creates proppants with high structural integrity and thermal stability. Post sintering, the proppants are cooled, checked for quality to ensure they meet necessary strength standards, and then graded for size. The method improves proppant quality by creating pellets that can withstand extreme subsurface pressures and temperatures without being crushed, offering the advantage of increased efficacy in fracking operations.

The process of sintering can be quite energy-intensive and requires precise control of various conditions, which could be seen as a disadvantage. The conventional method used for sintering ceramic proppants involves the usage of long rotary kilns that are fired with natural gas, making it expensive and time-consuming to construct and install. Additionally, it requires the installation of expensive scrubbers to reduce air emissions [65]. The process of sintering within a rotary kiln takes a long time, usually lasting from 30 min to over an hour to achieve the desired sintering temperature. However, if the temperature rises above the sintering temperature, the lower melting point minerals and metals present in the proppant tend to melt and form a coating within the kiln. This can lead to the shutdown of operations, which requires cooling and repairs, ultimately affecting the production capacity adversely.

4.2.1 Reported Proppant Enhancements as a Result of Sintering

Li et al. [66] conducted a study where they used pelletizing technology in preparing of low-density and high-intensity ceramic proppants. During the process, they also recycled



10% of waste ceramic sands. They investigated and optimized the sintering schedule, which included heating rate, holding time, and, sintering temperature to improve the microstructure, phase composition, and performance of the proppants. In conclusion, they determined that the proppants, when subjected to a sintering process at a temperature of 1260 °C for a duration of 2 h, with a heating rate of 5 °C per minute in the presence of air. These high-performance ceramic proppants, composed primarily of discarded ceramic sands and bauxite, exhibit great potential as fracturing proppants for application in the development of oil and gas.

Jianying et al. [67] successfully developed a low-density ceramic proppant by using solid waste coal gangue, and flint clay. The composition of the proppant primarily consisted of granular cristobalite and rod-shaped mullite. The proppant derived from solid waste coal gangue and calcined flint clay exhibited a lower density compared to the proppant derived from bauxite. Following sintering at a temperature of 1400 °C, the proppant's apparent density and bulk density were measured to be 2.79 g/cm³ and 1.27 g/cm³, respectively. The breakage ratio was determined to be 8.36% and 3.27% at closed pressures of 52 MPa and 35 MPa, respectively. This proppant fulfills the criteria of an optimal fracturing material. Furthermore, the use of coal gangue greatly decreases the expenses associated with the production of ceramic proppant and creates opportunities for the recycling of solid waste.

In another study, Qin et al. [68] investigated the effectiveness of inexpensive ceramic proppants with an additional 5 wt% Calcium carbonate at various sintering temperatures. The study reported that the quantity of liquid phase present in the proppants influenced the method of mass transfer, causing a transition from diffusion to flow mass transfer. The latter transfer facilitated the accelerated proliferation of mullite grains, leading to the formation of more compact samples. The investigation revealed that the most favorable dimensions of mullite crystal grains and the quantity of liquid phase reached an optimum level at a temperature of 1350 °C. At temperatures exceeding 1350 °C, the mullite crystal grains exhibited anomalous enlargement, and there was an excessive accumulation of liquid phase. The proppants that underwent sintering at a temperature of 1350 °C exhibited a bulk density of 1.42 g/cm³, which represents the highest density attained. Additionally, these proppants had the lowest breakage ratio of 8.41% when subjected to a closed pressure of 52 MPa. The results complied with the specifications of the Chinese Petroleum and Gas Industry Standards.

Zhao et al. [69] utilized dynamic sintering to produce low-density ceramic proppants from bauxite, manganese dioxide, and soft clay. The study examined the relationship between sintering temperature and the breakage ratio and the apparent density of the proppants. The specimens were investigated for their morphological structure and phase composition using X-ray diffraction (XRD) and scanning electron microscopy

(SEM). The findings indicated that the proppants consisted of glass phases and acicular mullite. Proppants derived from calcined bauxite demonstrated superior performance compared to those derived from natural bauxite. Elevating the sintering temperature led to enhanced crystallinity and a more compact microstructure. The proppants that underwent sintering at a temperature of 1355 °C demonstrated superior performance, characterized by an apparent density of 2.792 g/cm³ and a breakage ratio of only 3.22% under a pressure of 52 MPa.

4.2.2 Limitations and Challenges of Sintering

The process of sintering can be quite energy-intensive and requires precise control of various conditions, which could be seen as a disadvantage. The conventional method used for sintering ceramic proppants involves the usage of long rotary kilns that are fired with natural gas, making it expensive and time-consuming to construct and install. Additionally, it requires the installation of expensive scrubbers to reduce air emissions [65]. The process of sintering within a rotary kiln takes a long time, usually lasting from 30 min to over an hour to achieve the desired sintering temperature. However, if the temperature rises above the sintering temperature, the lower melting point minerals and metals present in the proppant tend to melt and form a coating within the kiln. This can lead to the shutdown of operations, which requires cooling and repairs, ultimately affecting the production capacity adversely.

4.3 Altering Surface Properties

4.3.1 Surface Modification Agent (SMA)

Surface modification of proppants implies altering the outer layer of proppant particles to improve their performance and interaction with the fracturing fluid and reservoir rock during hydraulic fracturing operations. This modification can enhance properties such as wettability, adhesion, conductivity, and resistance to embedment and crushing. Nguyen et al. [70] defined a surface-modification agent (SMA) as a polymer derived from sustainable sources. This polymer forms a coating on the proppant when introduced to aqueous solutions. The resulting residue is viscous and adhesive, with limited solubility in both oil and water. The utilization of SMA in conjunction with resin-coated proppants enables rapid resumption of production without the need for consolidation delays.

Lab experiments reported that proppants coated with SMA significantly enhanced the adhesive forces between individual grains and effectively impeded the process of settling. For example, when employing SMA in conjunction with 20/40-mesh Ottawa sands at closure stresses below 4,000 psi, there was an observed augmentation in both porosity and



permeability, leading to an enhanced proppant conductivity [70]. In addition, proppants coated with SMA do not undergo hardening, but instead maintain a sticky consistency, allowing them to endure repeated stress cycles. Due to its instantaneous effect, there is no need for a significant waiting period, making it compatible with aggressive flowback methods. In addition, the application of the SMA coating enhances the proppant's ability to withstand displacement, significantly raising the threshold flow velocity needed to cause fluidization and erosion of the proppant pack. The application of SMA coating enhances the efficiency of gel breakers in removing guar-based fluids, hence potentially enhancing fracture conductivity.

Tabatabaei et al. [71] suggested a method for applying a coating to the surface of pre-cured resin-coated sand proppants using hydrophobic graphite nanoplatelets (GNPs). These GNPs are available at a comparable cost to other coating materials commonly utilized in the industry. The scanning electron microscopy-energy dispersive X-ray spectroscopy (SEM-EDS) examination of proppants coated with graphene nanoplatelets (GNPs) revealed an uneven distribution of GNPs on the surface of pre-cured resin-coated sand proppants. The wettability of the proppants coated with GNP-resin was modified and demonstrated to be hydrophobic by testing performed according to ISO 13503-5:2006 [72] and API RP 19D [73] standards. Initial laboratory findings revealed an augmentation in both the efficiency and proportionate permeability of oil. The water-relative permeability of the proppants coated with graphene nanoplatelets (GNP) was found to be greater than that of the proppants coated with resin. The numerical simulation results indicate that GNP-coated proppants are very compatible with an oil-wet formation like Woodford Shale, but their effectiveness may be reduced in a water-wet formation. The enhanced proppants possess the capability to not only enhance but also expedite the process of fluid flowback during hydraulic fracturing, hence augmenting oil production.

A study conducted by Maley et al. [74] focused on enhancing the transportation and positioning of proppant through surface modification. Experimental results demonstrated that the proppant treated with the proppant transport modifier (PTM) additive exhibited many additional benefits, including reduced polymer adsorption, enhanced fluid recovery, and decreased proppant crushing. Furthermore, it has been discovered that the PTM addition is effective in altering the surface of the proppant in a wide range of high-salinity fluids, including recycled fracturing water, when the proppant is pre-treated. PTM has been demonstrated to provide a denser proppant pack, hence improving conductivity.

Proppant flowback is an unavoidable issue that occurs following a hydraulic fracturing treatment. Fu et al. [52] synthesized a surface-modified proppant by employing poly

(2-fluorine-4-vinylpyridine). This proppant showed an inherent ability to form aggregates in water, resulting in a substantial decrease in the rate at which proppant is carried back to the surface and a threefold enhancement in the ability of fractures to transport fluid. The modified proppants possess the ability to self-aggregate, which enables the reaggregation of fragmented proppants and formation of fines that have migrated. This reduces the likelihood of proppant flowback and the narrowing of the crack.

4.3.2 Plasma Treatment

Plasma treatment of proppants involves subjecting the proppant particles to a plasma discharge, typically in a low-pressure environment. This treatment alters the surface chemistry and properties of the proppant particles, leading to various improvements in their performance during hydraulic fracturing operations. Plasma treatment can enhance the wettability, adhesion, and compatibility of proppants with fracturing fluids, thereby improving their effectiveness in creating and maintaining fractures in the reservoir rock. Additionally, plasma treatment can modify the surface energy and roughness of proppant particles, which may enhance their ability to resist crushing and embedment under high-stress conditions in the fracture.

The researchers, Fan et al. [75], effectively created a novel variety of permeable proppants. This proppant possesses a rigid outer layer and sealed pores, and it was manufactured via rapid sintering utilizing thermal plasma and closed-external pore sintering employing a rotating kiln. The researchers utilized low-grade bauxite as a raw material, which is typically discarded as a waste resource. They discovered that the proppant's breakage ratio was 6.9%, its permeability was $163.57 \mu\text{m}^2$ at 52 MPa, its short-term fracture conductivity was $102.15 \mu\text{m}^2/\text{cm}$ and its optimum apparent density was 1.25 g/cm^3 , after conducting tests. These qualities were attained by employing concentrations of 13.4 weight percent micro-silica, 6.2 weight percent sodium metasilicate, and 5 weight percent nano-silica, together with a post-sintering temperature of 1200°C . The proppant possesses the necessary characteristics to fulfill the specifications of hydraulic fracturing technology, eliminating the necessity for suspending agents. This offers a more ecologically sustainable method of extracting the global reserves of shale oil and gas.

Plasma surface treatments are mostly applied to polymers. These polymers are later applied on the surfaces of these proppants as coatings. Plasma treatment of polymers involves a variety of plasma technologies and polymeric materials for various applications. For instance, Grace and Gerenser [76] recommend using low-radio-frequency capacitively coupled nitrogen plasmas to achieve high plasma densities and reactive species populations for effective plasma treatments on

various materials. Surface chemical analysis of modified polymers, including polyesters, has been investigated in nitrogen plasmas generated by capacitive coupling at a frequency of 40 kHz. In plasma treatments, the shift from reaction-limited kinetics to diffusion-limited kinetics occurs. However, the specific diffusing species in nitrogen plasma treatment of polyesters remains unidentified. The chemical structure of a polymer can impact the surface chemistry achieved during plasma treatment, resulting in varying rates of incorporation of new chemical species for various polymers.

Hegemann et al. [77] reported that polymer surfaces can undergo various modifications through plasma treatment such as etching, cleaning, activation, and cross-linking. This process can be used to enhance wetting qualities, improve adherence to plasma-deposited coatings, and minimize friction. Depositing coatings is frequently advantageous for customizing the surface characteristics of polymers. Plasma-deposited layers must have high adhesion to polymers to prevent the quick deterioration of stressed components. Depositing graded layers or ultra-thin films typically enhances adhesion. Plasma treatment should be tailored for various polymers to reduce degradation and aging effects. All structures, especially purposefully modified surfaces, are prone to aging.

4.3.3 Limitations and Challenges of Altering Proppants Surface Properties

The effectiveness of surface modification agents can be highly dependent on the specific interactions between the agent and the proppant material, requiring extensive customization and testing for each application. Additionally, the long-term stability of the modified surface under downhole conditions is a challenge, as exposure to high pressures, temperatures and chemical environments can degrade the modification, reducing its effectiveness.

Achieving uniform plasma treatments across all proppant particles can be difficult, leading to variability in performance. Additionally, plasma treatments can be time consuming, potentially slowing down the production process. More so, the long stability of plasma-modified surfaces in the harsh downhole environment is uncertain, as exposure to extreme conditions may reverse or degrade the modifications. It should be noted that scaling up the plasma treatment process for large volumes of proppants used in hydraulic fracturing can be technically challenging and economically prohibitive.

4.4 Consolidation

Proppant consolidation is implemented in hydraulic fracturing to retain proppants in place within the induced fractures.

The main function of the consolidated pack in hydraulic-fracturing applications is to inhibit the movement of the proppant back to the surface. Norman et al. [78] proposed that compressive strengths of approximately 150 psi would be sufficient to manage proppant flowback during high-production rates in fracturing applications.

Dewprashad et al. [79] conducted a study comparing the consolidation abilities of resin-coated proppants (RCPs) with varying cure kinetics in settings mimicking extended pump periods and delayed or inadequate fracture closures in well packs. The methods used to analyze RCPs' cure kinetics were differential scanning calorimetry (DSC), rock-mechanical studies, and scanning electron microscopy (SEM). The cure kinetics of the resin coats on proppants have a major impact on their final downhole consolidation strengths and performances. Proppants coated with resin and cured at 230 °F exhibited significantly greater strength compared to those cured at 150–200 °F for 20 h. Consolidation strength decreases progressively as pump times increase. High-temperature liquid resin-coated proppants exhibited significantly stronger consolidations without closure circumstances. This makes them more appropriate for treatments involving gradual fracture closures and results in more densely consolidated packs, even in regions with minimal closure.

Nguyen et al. [80] devised two techniques for consolidating proppant particles. One method was utilizing a liquid resin that can be hardened and a liquid agent that induces hardening, employing various combinations of resin and agent ratios. The liquid hardening agent component included a hydrolyzable ester. This hydrolyzable ester was responsible for disrupting the gelled fracturing fluid films present on the proppant particles. Another technique involved using a hydrolyzable ester, such as dimethyl glutarate, dimethyl adipate, and dimethyl succinate, to disrupt the solidified films of fracturing fluid on the proppant particles. The objective of these techniques was to generate compacted permeable proppant formations within the fractures that possess excellent fluid conductivity of the formation and effectively hinder the movement of proppant or the passage of tiny particles from the formation.

Vo et al. [81] conducted a study to achieve delayed consolidation and agglomeration features of the proppant pack. The study coated proppants with a resin mixture consisting of a tackifier polymer, a catalyst, and curable resin before mixing the coated proppant grains into a fracturing fluid. Once the coated proppant was placed, consolidation levels were seen to rise with time and temperature. By integrating the delayed consolidation and agglomeration qualities into one proppant coating, it is possible to immobilize the proppant and prevent formation sand and fines movement, thereby significantly improving and maintaining proppant pack conductivity. The



Liquid Curable Resin-coated proppant pack has strong consolidation strength to prevent proppant flowback in harsh environments and preserve good fracture conductivity.

4.4.1 Limitations and Challenges of Proppant Consolidation

One major issue with consolidation is ensuring consistent and strong bonding between particles, as weak spots can lead to proppant pack failure under high pressure. The materials and processes used for consolidation must be carefully chosen to avoid negatively impacting the permeability and conductivity of the proppant pack. The cost and complexity of consolidation processes can be higher than traditional proppant treatments, potentially limiting their widespread adoption.

4.5 Mixing of Proppants

This technique relates to the process of combining different types or sizes of proppants to be injected in hydraulic fracturing operations. Researchers have applied this method to optimize fracture performance, reduce costs, maximize well productivity based on formation characteristics, enhance proppant transport, and mitigate proppant flowback. Hybrid completion designs sometimes involve combining different sizes of proppant depending on stimulation design assumptions and criteria. According to Liang et al. [1] combining different sizes of proppant in stimulation treatments may decrease permeability since the finer particles can infiltrate and fill up the pore spaces between the larger ones. Nevertheless, several studies supported the proppant mixing approach for observed performance enhancements.

Schmidt et al. [13] examined the behavior of different proppant sizes mixture. They examined factors such as the viscosity of the fracturing fluid and the settling rates of the proppants since they lead to different distributions within the fracture, from segregated layers to evenly mixed blends. It was found that higher concentrations of more conductive proppants substantially increase the conductivity of propped fractures. Specifically, using 40/80 lightweight ceramic (LWC) as a smaller size proppant instead of 40/70 sand results in significantly higher conductivity. In addition, the inclusion of larger-size LWC proppants mixed with 40/70 sand improves the conductivity of the overall proppant pack, irrespective of the concentration used. Furthermore, the decision between using 20/40 LWC and 30/50 LWC does not significantly affect conductivity under most conditions when these are used with 40/80 LWC. The study also found out that the generation of fines and their potential migration did not seem to permanently degrade the conductivity of the proppant pack when the fluid flow was increased from 2 to 100 mL/min. Finally, low concentrations of 40/70 sand mixed with larger-size LWC proppants achieved nearly the same

conductivity as high concentrations of 40/80 LWC mixed with larger-size LWC.

Another study by Hu et al. [82] provides a detailed analysis of the impact of different proppant types on the long-term production and economic effectiveness of hydraulic fracturing wells. The study included data from 72 wells across four different fields, focusing on the percentage and amount of each proppant type used. It was found that in the Upland Field (North Dakota, USA) case study, wells using a mix of ceramic proppant and sand showed an 11% increase in cumulative production over 270 days compared to wells using a mix of resin-coated sand and sand. The initial extra cost for ceramic proppant was recouped in less than 270 days due to higher production.

Jianguang et al. [83] conducted an experimental study on the long-term fracture conductivity using quartz sand, which included the mixing of proppants and applying closing pressure. Proppants with three different particle sizes were chosen: 20–40 mesh, 40–70 mesh, and 70–140 mesh. The ingredients were combined based on a certain ratio to create a mixture of proppants, which were then used to assess the long-term fracture conductivity. The proppants' mixing technique adhered to the forward segmentation approach in studying the correlation between mixture ratio and long-term fracture conductivity. It was found that uniformly mixing proppants does not effectively enhance fracture conductivity, whereas forward segmentation of proppant sizes is more beneficial. Additionally, a decrease in particle size with increasing closing pressure, affects fracture conductivity negatively. Furthermore, a significant decline in long-term fracture conductivity was noted, especially with higher proportions of certain mesh-size particles, suggesting that proppant breakage under pressure is a critical factor.

4.5.1 Limitations and Challenges of Mixing of Proppants

One major challenge of mixing proppants is achieving a homogeneous mixture of proppants with different physical properties, such as size, shape, and density. Inconsistent mixing can lead to segregation during transport and placement, resulting in uneven proppant distribution within the fractures. This can reduce the effectiveness of the proppant pack, leading to lower permeability and conductivity, and ultimately, less efficient hydrocarbon extraction. The mixing process itself must be carefully controlled to ensure uniformity, which can be technically complex and costly.

In addition, mixing proppants have the potential for compatibility issues between different proppant types. For example, mixing natural sand with ceramic proppants or resin-coated proppants may result in unexpected chemical reactions or physical interactions that degrade the performance of the proppant pack. Ensuring that all mixed proppants maintain their integrity and performance characteristics

under downhole conditions is crucial, yet challenging. This requires extensive testing and validation, increasing the time and cost of the fracturing operation.

Another aspect is that the cost of high-performance proppants, such as ceramic or resin-coated types, is significantly higher than that of natural sand. Mixing these with cheaper proppants can help reduce costs, but the potential benefits must be carefully weighed against the risk of reduced performance or increased operational complexity. Companies must conduct detailed cost–benefit analyses to determine the optimal mix ratio that balances performance improvements with cost efficiency.

Finally, different proppants may have varying environmental footprints in terms of sourcing, production, and disposal. Managing the environmental compliance of mixed proppants can be more complex than dealing with a single type, particularly if the mixture includes materials with different regulatory requirements. Ensuring that all proppants in the mix meet environmental standards adds another layer of complexity to the operation.

5 Economic Considerations of the Different Proppant Types

Since the experimental fracturing job in the Hugoton field in 1947, which utilized sand from the Arkansas River, sand has continued to be the predominant proppant in hydraulic fracturing due to its economic benefits. Typically, frac sand is not used in its raw, mined state but undergoes additional processing to enhance its performance. This processing involves extracting material from silica sand deposits, followed by crushing, washing and cleaning, drying, and sizing the sand grains [84, 85].

Due to sand's inability to endure high closure stresses of up to 6000 psi, stronger ceramic proppants were developed and introduced to the market. These ceramic proppants are produced from sintered bauxite, kaolin, magnesium silicate, or combinations of bauxite and kaolin. As an engineered product with a more complex manufacturing process, ceramic proppants are more expensive than both uncoated and resin-coated sand [1].

The expenses associated with chemicals for coating or altering the surface properties of proppants can significantly impact the overall cost structure of hydraulic fracturing operations [10]. These chemicals, including resin polymers and other specialized coatings, are designed to enhance the performance characteristics of proppants, such as reducing flowback and increasing conductivity under high-stress conditions. However, the production and application of these coatings introduce additional costs [86]. For instance, the cost of resin-coated sand can be up to three times higher than that of uncoated frac sand [87]. Similarly, advanced

surface modifications, such as nanocomposite coatings, further increase the cost due to their complex manufacturing processes. Despite these higher costs, the enhanced performance and potential reduction in the frequency of fracturing treatments can lead to long-term economic benefits, justifying the initial investment in many scenarios.

The selection of proppants in hydraulic fracturing is a crucial economic and technical decision that significantly influences stimulation and field development economics. The primary goal in designing the stimulation process is to maximize well production while also considering the minimization of completion costs. The choice of proppant directly affects the overall job economics, treatment size, and the well's ultimate productivity. This decision is typically guided by balancing well production through estimates of dimensionless fracture flow capacity (F_{CD}) and stimulation cost. Since proppant cost constitutes a substantial portion of well treatment expenses, the ultimate objective in selecting the appropriate proppant is to maximize the net present value (NPV) for a given well.

A longer and more conductive hydraulic fracture will achieve more production than a smaller, less conductive fracture. However, fracture treatment design is a trade-off between increased cost of adding length and conductivity, and the economic benefits of the resulted increase in production. Most of the approaches used for cost–benefit based optimization of fracture design vary parameters such as fluid and proppant volumes, concentrations, types and flow rates. Proppant cost is a significant portion of a well treatment cost. For a small sand proppant treatment design, the proppant may account for 10–20% of the total cost of the treatment; whereas, in a large treatment using synthetic manufactured proppant, the proppant cost can be in excess of 50% of the total cost.

Yang et al. [88] conducted a statistical study on reservoirs in the Wolfcamp/Clearfork basin, focusing on proppant type selection, optimization of proppant quantity, and proppant mesh size. They found that wells using natural sand proppants save on completion costs compared to ceramic proppant wells, while production levels remain similar.

Mack and Coker [89, 90] emphasized that the economic metrics of net present value (NPV), internal rate of return (IRR), and the payout time should all be considered in unconventional reservoirs. These metrics often lead to similar capital allocation decisions because 30–40% of the estimated ultimate recovery from unconventional wells occurs within the first two years. They developed an economic model to calculate NPV, IRR, and payout time, which uniquely incorporates revenue from oil and gas production using an assumed decline curve. Assuming the initial investment cost rises by “ C ” when replacing sand with upgraded proppant and the production increases by “ P ” in percentage, the required percentage production increase to offset the cost is



calculated using Eq. 6.

$$P\% = \frac{C}{NPV + \text{Well Cost}} \quad (6)$$

In summary, the choice of proppant should be guided by economic optimization. Ceramic proppant should be chosen over sand only if there is a clear economic benefit.

6 Environmental Considerations of the Different Proppant Types

The environmental impact of different types of proppants, including sand, resin-coated sand, and ceramic proppants, varies based on their extraction, processing, use, and disposal. The mining of silica sand can cause significant land disturbance and habitat loss, as well as risks of water contamination and air pollution due to the release of fine particulate matter (silica dust) that can lead to respiratory problems [91–93]. The washing and processing of sand requires large volumes of water, potentially impacting local water supplies and aquatic ecosystems. While sand proppants are relatively inert, they are often used with chemical additives in the fracking fluid, posing environmental risks if they contaminate groundwater or surface water. Used sand proppants can accumulate on the surface or in disposal sites, potentially leading to soil and water contamination if not properly managed.

The production of resin-coated sand involves the application of resin polymers, which introduces additional chemicals into the environment. This production process may release volatile organic compounds (VOCs) and other pollutants [94]. Resin-coated sand is designed to reduce proppant flow-back and improve conductivity, potentially reducing the frequency and intensity of fracking operations, which can help mitigate some environmental impacts associated with repeated fracking. However, it's important to note that the resin coating can break down over time, possibly releasing chemicals into the environment. Proper disposal and management are necessary to minimize these risks.

The manufacturing of ceramic proppants involves high-temperature processing and significant energy consumption. The mining and processing of these materials can result in considerable environmental degradation, including habitat destruction, and water and air pollution. The energy-intensive production process contributes to a higher carbon footprint compared to sand proppants. However, due to their durability, ceramic proppants can withstand higher pressures, potentially reducing the need for frequent re-fracturing. This durability can lessen the cumulative environmental impact over the lifespan of a well. In addition, ceramic proppants may have a longer life cycle and could potentially be reused, reducing the need for continuous extraction and production.

Nevertheless, their disposal still needs to be managed to prevent environmental contamination. Table 5 summarizes the different proppant enhancement methods.

7 Future Research and Development in Proppant Technology

Future research and development in proppant technology can focus on several promising areas to enhance efficiency and overall performance in hydraulic fracturing. This promising research can greatly transform the oil and gas industry into a direction of increased production and higher recovery of unconventional reservoirs.

7.1 Advanced Coatings

Developing biodegradable or more environmentally benign coatings to reduce ecological impact can be research for future development in proppant technology. Additionally, Self-healing Coatings that can self-repair small cracks and damage, extending the life and effectiveness of the proppant is possible as to conduct as future research. To date, extensive research has been initiated in order to identify new biodegradable polymer materials which could fulfill all the features needed for the desired quality of the eco-friendly polymeric coating materials [95].

7.2 Nanotechnology

Nanoparticle infusion which involves incorporating nanoparticles to enhance strength, reduce fines production, and improve the proppant's thermal and chemical resistance is a potential future research development in proppant technology as discussed by Mao et al. [96]. Using nanotechnology to create proppants with superior wettability and flow characteristics, optimizing their performance in different reservoir conditions can be considered for future promising research area.

7.3 Material Innovation

Developing high-strength, low-density proppants that can be transported more efficiently and remain suspended in fracturing fluids longer is a promising future research direction in proppant technology. Research by Liao et al. [97] provides a thorough analysis of lightweight proppants which are hollow, porous, surface modified, and those that are derived from low density materials. Creating new synthetic materials that offer superior strength, durability, and environmental performance compared to traditional sand or ceramic proppants stands to be another future research in proppant technology.

Table 5 Assessment of the proppant enhancement methods

Proppant enhancement methods		Performance enhancement		Economic		Environmental	
		Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages
Coating with polymers	Thermoplastic coating	Coating proppants with a 0.01–15% concentration of the proppant's weight reduces proppant flowback	Performance may degrade at very high temperatures	Extends the lifespan of proppants, reducing the frequency of replacements	Specialized equipment and processes required	Reduces proppant replacement frequency, lowering overall resource consumption	Potential environmental impact from the disposal
	Fluorinated coating	Provides chemical resistance and hydrophobic properties	Limited temperature resistance Potential for chemical degradation over time	Potentially lower costs associated with chemical damage and maintenance	High cost of fluorinated materials Potentially expensive application process	Minimizes the risk of proppant degradation and subsequent environmental contamination.	Environmental concerns regarding the disposal
Inorganic coating	Inorganic coating	Provides excellent thermal stability and chemical resistance	May not bond as effectively as organic coatings	Long-lasting performance can reduce replacement frequency	Application process can be complex and costly	Often made from naturally occurring materials	Potential environmental impact during mining and processing
	Hydrogel coating	Provides temporary water retention and release properties Can reduce friction and improve fluid flow	Limited long-term stability under high pressures and temperatures	May enhance efficiency of hydraulic fracturing, reducing overall costs	Additional costs for hydrogel materials and application	Biodegradable options can minimize environmental impact	Potential for environmental contamination if not biodegradable



Table 5 (continued)**Proppant enhancement methods**

Method	Performance enhancement		Economic		Environmental	
	Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages
Sintering	Magnetic coating	Allows for controlled placement and retrieval of proppants	May not bond as effectively as organic coatings	Reduces the need for chemical tracers and other monitoring technologies	Can minimize impact by reducing chemical usage	Disposal may have environmental implications
		Increases the strength and durability of proppants Reduces fines generation under high pressure	High-temperature process can be energy-intensive	Longer-lasting proppants reduce replacement frequency	Can use recycled materials, reducing waste	Significant energy consumption can increase carbon footprint
Altering surface properties	Surface Modification Agent (SMA)	Can improve surface wettability and adhesion Enhances compatibility with fracturing fluids	May require reapplication or reinforcement over time	Can improve efficiency of hydraulic fracturing operations	Additional costs for surface modification agents	Potential environmental impact from the disposal of modification agents
	Plasma treatment	Enhances surface properties without additional materials Increases proppant strength and chemical resistance	Effectiveness can be limited by high pressures and temperatures	Can improve proppant performance, reducing operational costs	High initial investment in plasma treatment equipment	Energy-intensive process can increase carbon footprint



Table 5 (continued)

Proppant enhancement methods						
Method	Performance enhancement		Economic		Environmental	
	Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages	Advantages	Limitations/disadvantages
Consolidation	Binds proppants together to reduce flowback	May affect permeability and fluid flow in some cases	Reduces the need for maintenance and replacements	Additional cost for consolidation materials and processes	Can minimize environmental disruption by reducing proppant loss	Potential environmental impact from the use and disposal of consolidation agents
	Improves proppant pack integrity and stability					
Mixing proppants	Combines benefits of different proppant types to optimize performance	Compatibility issues between different proppant types can arise	May reduce costs by using a blend of lower-cost and higher-performance proppants	Potentially higher costs due to the need for multiple types of proppants		Mixed proppants can complicate recycling and disposal efforts
	Can tailor proppant mix to specific reservoir conditions					



7.4 Smart Proppants

Developing proppants with sensing capabilities is potential future research. This might involve embedding sensors within proppants to monitor downhole conditions such as pressure, temperature, and fracture geometry in real-time. Responsive Proppants can be designed to change their physical properties such as expanding and contracting in response to specific stimuli, optimizing fracture conductivity dynamically.

8 Conclusions

The performance of proppants plays a pivotal role in the success of hydraulic fracturing operations. A thorough evaluation of proppant performance necessitates an in-depth understanding of proppant properties and the factors influencing their behavior during the fracturing process. The selection of the most suitable method depends on the reservoir conditions, the proppant properties, and the operational constraints. The design of a hydraulic fracturing treatment is a critical step in optimizing the well productivity, and it involves the selection of the proppant type and concentration, the evaluation of the fluid properties, and the analysis of the fracture geometry. A thorough understanding of the proppant properties and the factors that affect their behavior in the fracturing process is necessary to develop effective fracturing treatments that maximize the well productivity and enhance the recovery of hydrocarbons. Selecting the most appropriate proppant type and optimizing proppant properties are essential for maximizing fracture conductivity and enhancing well productivity. This underscores the need for a comprehensive study of proppant evaluation and enhancement techniques.

In this work, we provided a detailed examination of the three primary proppant types used in the industry: silica sand, ceramic proppants, and resin-coated proppants. By exploring the advantages and disadvantages of each type, we aimed to facilitate better decision-making in proppant selection. We also reviewed various proppant evaluation techniques, detailing their methodologies and the properties they assess. Furthermore, we explored several proppant performance enhancement methods, including polymer coating, sintering, surface property modification, and proppant mixing, highlighting their impacts on key proppant performance criteria.

The added value of this review lies in its comprehensive evaluation of both the performance and the economic and environmental implications of various proppant enhancement techniques. This work not only provides a detailed comparison of proppant types and enhancement methods but also offers a critical analysis of their sustainability

and cost-effectiveness. This comprehensive review lay the groundwork for future research aimed at optimizing proppant selection and treatment strategies, with a focus on achieving both technical efficiency and environmental sustainability in hydraulic fracturing operations.

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